

A model study of the impact of magnetic field structure on atmospheric composition during solar proton events

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[1] During a polarity transition of the Earth's magnetic field, the structure and strength of the field change significantly from their present values. This will alter the global pattern of charged particle precipitation into the atmosphere. Thus, particle precipitation is possible into regions that are at the moment effectively shielded by the Earth's magnetic field. A two-dimensional global chemistry, photolysis and transport model of the atmosphere has been used to investigate how the increased particle precipitation affects the chemical composition of the middle and lower atmosphere. Ozone losses resulting from large energetic particle events are found to increase significantly, with resultant losses similar to those observed in the Antarctic ozone hole of the 1990s. This results in significant increases in surface UV-B radiation as well as changes in stratospheric temperature and circulation over a period of several months after large particle events.

INDEX TERMS: 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 1535 Geomagnetism and Paleomagnetism: Reversals (process, timescale, magnetostratigraphy); 1650 Global Change: Solar variability; 2716 Magnetospheric Physics: Energetic particles, precipitating. **Citation:** Sinnhuber, M., J. P. Burrows, M. P. Chipperfield, C. H. Jackman, M.-B. Kallenrode, K. F. Künzi, and M. Quack, A model study of the impact of magnetic field structure on atmospheric composition during solar proton events, *Geophys. Res. Lett.*, 30(15), 1818, doi:10.1029/2003GL017265, 2003.

1. Introduction

[2] Solar energetic particle events have been identified as sources of potential ozone loss in the middle atmosphere already in the 1970s. It was recognized that the ionization and dissociation of the neutral atmosphere, induced by charged particle precipitation, leads to the formation of NO_x (N, NO, NO₂) [Crutzen *et al.*, 1975; Porter *et al.*, 1976]. A similar process involving ion chemistry was proposed for the production of HO_x (H, OH, HO₂) from water cluster ion formation and subsequent neutralization [Swider and Keneshea, 1973; Solomon *et al.*, 1981]. Both NO_x and HO_x destroy ozone in catalytic cycles. The formation of NO_x and the subsequent ozone loss have been measured during several large particle events, and are

reproduced by atmospheric chemistry models fairly well [Solomon *et al.*, 1983; Jackman *et al.*, 2001]. While local ozone losses during a particle event can be very large (e.g., [Jackman *et al.*, 2001]), the impact on total ozone is negligible, as most energy is deposited above 40 km altitude, well above the ozone layer. However, it has been speculated by some authors that significant losses of total ozone may occur several weeks or months after particle events due to the slow downward transport of the long-lived NO_x species [Jackman *et al.*, 1990; Jackman and Fleming, 2000; Callis *et al.*, 1998]. Indeed, enhanced values of NO_x have been observed in the southern polar lower stratosphere several weeks after a large particle event [Randall *et al.*, 2001]. During the period covered by global observations of ozone, the impact of even the largest particle events on the total amount of ozone has been small compared to the dynamical variability of ozone, and to anthropogenic induced phenomena such as the Antarctic 'ozone hole' (e.g., compare data from WMO [1999] to results from Jackman *et al.* [1995; Jackman and Fleming, 2000]). This is largely explained by the shielding effect of the Earth's magnetic field. Solar energetic particles are deflected by the magnetic field, and can precipitate down into the atmosphere only into the polar caps 30° around the magnetic poles. However, there is recent evidence that the Earth's magnetic field may be approaching a reversal [Hulot *et al.*, 2002]. Polarity reversals of the Earth's magnetic field have occurred at irregular intervals of about 200,000 years. For several thousand years during the reversal process, the dipole strength of the magnetic field decreases to values lower than 25% of the mean value, and the field topology is no longer dominated by its dipole components [Merrill and McFadden, 1999]. The last reversal is now 780 ka ago, and the currently decreasing dipole moment [McElhinny and Senanayake, 1982] and field inhomogeneities [Hulot *et al.*, 2002] may be an indicator that another polarity transition will occur in the next thousand years. The question of whether a decrease of magnetic field strength would lead to a significant increase of ozone loss after large particle events has been discussed in the past [Reid *et al.*, 1976; Hauglustaine and Gerard, 1990]. Both studies used 1 D models to investigate the globally averaged change of ozone during a particle event; they did not take into account the latitudinal and temporal evolution of the event. Furthermore, both studies could only make rough estimates of what a 'very large' particle event might be like. In the intervening years, new information about the nature of particle events has been gathered. Important evidence about the magnitude and frequency of large particle events was derived very recently from ice-core depositions of nitrate that reach back 400 years in the past [McCracken *et al.*, 2001a, 2001b]. These data show that solar energetic particle

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production is low at the moment, and was considerably larger for example in the second half of the 19th century. Evidence was found in the ice-core data for solar proton events which were several times larger than the largest event observed since reliable global data from satellites have been available—from October 19 to October 27, 1989. In addition, periods where as many as five events of the same magnitude as the October 1989 event occurred in the course of three years could be identified in the ice-core record. The current solar maximum seems to be fairly active as well, with five very large solar proton events in the course of 17 months, on July 14, 2000, November 9, 2000, September 25, 2001, November 6, 2001 and November 23, 2001. This information enables us to provide more realistic estimates about the possible magnitude of very large particle events, and thus to develop realistic ‘worst case’ scenarios for particle events during magnetic polarity transitions.

2. Model Description

[3] A global 2 D photochemical and transport atmospheric model has been used to investigate the impact of very large particle events on total ozone, and their dependence on the constitution of the magnetic field. The model used is a composite of the 2 D meteorological module THIN AIR [Kinnersley, 1996] and the chemical module SLIMCAT [Chipperfield, 1999]. It calculates temperature, pressure, photolysis rates, transport and the behavior of 57 chemical species on isentropic levels with a vertical resolution of about 3 km and a horizontal resolution of 9.47° . The model uses reaction rates and absorption cross sections from the JPL 2000 recommendation [Sander *et al.*, 2000]. We use the NO_x and HO_x production as a function of atmospheric ionization that is given in Jackman *et al.* [1990]. For all model runs, the initialization of chemical species assumed a pre-industrial scenario, i.e. emissions of greenhouse gases such as CO₂, CH₄ and N₂O, as well as source gases of chlorine, bromine and fluorine, were set to values typical for 1850 [WMO, 1999]. This was done in the first place to account for paleo-historic scenarios, and secondly, to inhibit interference of particle-produced NO_x with reactive chlorine, thus decreasing polar ozone loss as discussed in a recent study [Jackman and Fleming, 2000]. Ionization profiles were calculated from proton flux energy spectra provided by the GOES 7 satellite instrument. Ionization rates were calculated from the proton energy deposition as described, e.g., in [Jackman *et al.*, 1980].

3. Model Scenarios

[4] The study is based on two assumptions. First, that during a magnetic polarity transition the shielding effect of the magnetic field decreases so that high-energetic charged particles can precipitate into the atmosphere equally everywhere, not only into the polar caps as today. Second, that solar energetic particle production may be considerably larger in the future than at the moment. The first assumption gives one rather extreme case for the Earth’s magnetic field during a reversal. It assumes a dipole dominated field that vanishes completely during the reversal process. The second assumption is based on the ice-core data of McCracken *et al.* [2001a, 2001b], and realistic scenarios for very large particle events

Table 1. Description of Model Scenarios With Various Particle Event and Earth’s Magnetic Field Combinations

Scenario	Particle Event(s)	Magnetic Field
Base	None	Present day
A	October 1989	Present day
B	October, November, and July events equal to October 1989	Present day
C	October, November, and July events equal to October 1989	Greatly reduced

have been derived from these data. Three scenarios were tested with a ‘normal’ magnetic field: 1) a “Base” scenario with no particle events; 2) scenario “A” where the atmospheric energy deposition is equal to the October 1989 event; and 3) scenario “B” with three events of the same magnitude and duration as the October 1989 event in the course of ten months. This scenario was chosen to provide realistic particle energy spectra while at the same time giving an estimate for ‘worst case’ scenarios of solar energetic particle precipitation. All scenarios with a ‘normal’ magnetic field allow precipitation of charged particles only into the polar caps. Ionization profiles for every latitude were weighted by the relative area of the latitudinal belt that lies inside the polar caps. An additional scenario “C” was carried out that was similar to scenario “B” with three ‘October 1989’ events. Scenario “C” assumes that the magnetic field strength has decreased significantly, and charged particles can precipitate into the middle atmosphere equally in all latitudes. Identical ionization profiles were used for all latitudes. The scenarios are all listed and briefly defined in Table 1.

4. Results and Discussion

[5] The change of NO_y (N, NO, NO₂, NO₃, HNO₃, HO₂NO₂, ClNO₃ and 2 * N₂O₅) due to particle events for model scenarios “A”, “B”, and “C” was calculated by comparing to the “Base” scenario. The resultant excess NO_y is shown in Figure 1 for a position well inside the polar caps at 76°N . Significant values of NO_y are formed only in a period of a few days during the particle events. However, NO_y is rather long-lived in the high-latitude middle atmosphere, so enhanced values of NO_y persist for weeks and even months after large particle events. Significant values of NO_y are produced only at altitudes above 40 km, but eventually, in the polar winter vortices NO_y is transported down to altitudes below 30 km. Though the NO_y production in polar regions is the same in model runs “B” and “C”, in model run “C” the excess NO_y in polar regions is much larger due to horizontal transport of NO_y from mid-latitudes and tropical regions. Above around 40 km, catalytic cycles with HO_x are more effective for ozone loss, and the initial large local ozone losses during particle events are more likely to be caused by the short-lived excess HO_x than by NO_x. However, below 30 km altitude, where ozone concentrations are largest, catalytic cycles with NO_x species contribute significantly to ozone loss. A long-term impact of large particle events with respect to total column ozone is therefore expected from the modeled slow downward transport of excess NO_y. The change of total ozone was calculated for model scenarios “A”, “B”, and “C” by comparing to the “Base” scenario (see Figure 2). In all model cases, significant ozone changes are confined mainly to Polar Regions $>50^\circ$. The largest impacts of the particle events

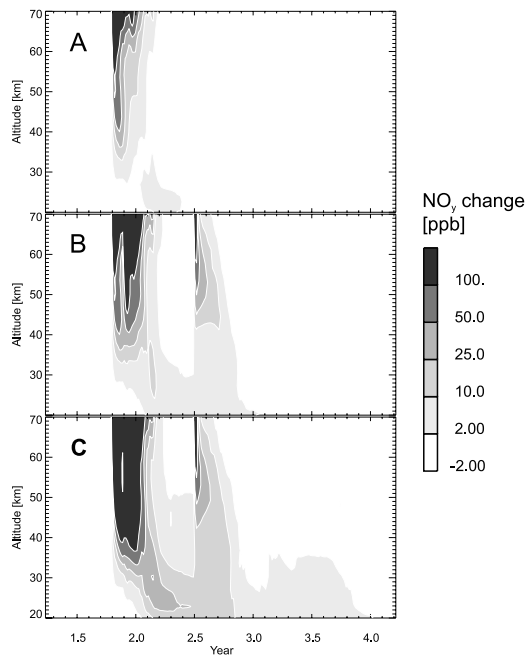


Figure 1. Modeled excess NO_y at 76°N due to large particle events: A) for scenario “A”, the October 1989 event; B) for scenario “B”, a series of three events of the same magnitude as the October 1989 event, and C) for scenario “C”, the same as “B” but with a strongly reduced magnetic field. The date 1.0 is the first of January of the first model year. A summary and description of the model scenarios can be found in Table 1.

on total ozone occur several months after the first event in every case. This results from the slow downward transport of NO_x in the polar winter vortices. Ozone losses are largest in the Northern Hemisphere because the particle events occurred during northern autumn and early winter, when downward transport is most efficient. The ‘worst case’ scenario “B” shows total losses of ozone that are significantly larger than for the October 1989 event. However, the modeled changes of 10–15% in the polar regions are in the order of magnitude of dynamical changes, smaller than the anthropogenic-induced ‘ozone hole’. For scenario “C” with a strongly reduced magnetic field, losses of total ozone reach values of 45–50%, of the order of magnitude as observed in the 1990s in the Antarctic ‘ozone hole’ [WMO, 1999]. Even though particle precipitation and the resulting NO_x formation were allowed in all latitudes in this model scenario, the ozone loss is still confined mainly to polar regions, because of the global transport patterns of the middle atmosphere: Large-scale downward transport occurs only in the polar winter vortices, so enhanced values of NO_x can be transported down into the ‘ozone layer’ only in polar winter and spring.

[6] The large ozone depletion following the events for case “C” will lead to an increase of surface UV-B radiation. We estimate the erythemal weighted UV-B increases by applying a radiation amplification factor of 1.1 using a simple empirical relationship between ozone column change and UV-B increase [WMO, 1999]. In midlatitudes erythemal UV-B increases by about 10% with a maximum in late summer and autumn of the second model year. In polar

regions UV-B increases by more than 60% with a maximum during summer of the second model year and about 20% during the following summer.

[7] *Haughustaine and Gerard* [1990] argue that during very large particle events, the surface radiation around 400 nm can decrease significantly due to the greatly increased NO_2 absorption. Like *Haughustaine and Gerard* [1990], we also find an increase of NO_2 column density of about two orders of magnitude for scenario “C”. However, in our model scenario, the largest increase occurs not during the event, but some time later, and only during polar winter. There, NO_2 column densities are considerably smaller than the midlatitude values given by *Haughustaine and Gerard* [1990], and the absolute increase of NO_2 column from about $1 \times 10^{14} \text{ cm}^{-2}$ to about $1 \times 10^{16} \text{ cm}^{-2}$ is not large enough to influence the ground radiation much even around 400 nm, where NO_2 absorption is largest.

[8] Ozone is one of the major contributors to radiative heating in the stratosphere, so large decreases of stratospheric ozone will lead to a cooling of the stratosphere. The effect of changes in radiative heating on temperature are considered in the THIN AIR model, and the temperature changes between the Base run and the ‘worst case’ scenario “C” are shown in Figure 3, exemplarily for a latitude of 76°N . Large differences in the modeled temperatures are observed, with a cooling of more than 6 K in the upper stratosphere and mesosphere in the weeks following the large particle events, and in the lower stratosphere starting some time after the first event and lasting for several months. At the same time, a warming of 3 to 6 K is observed in the altitude region from 30 to

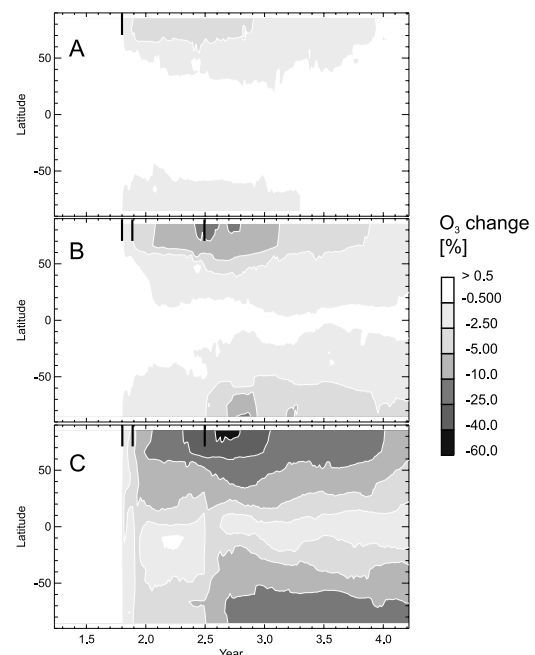


Figure 2. Modeled change of total ozone as a function of latitude: A) for scenario “A”, the October 1989 event; B) for scenario “B”, a series of three events of the same magnitude as the October 1989 event within ten months; and C) for scenario “C”, the same events as scenario “B” but with a strongly reduced magnetic field. Thick black lines indicate the occurrence of solar proton events.

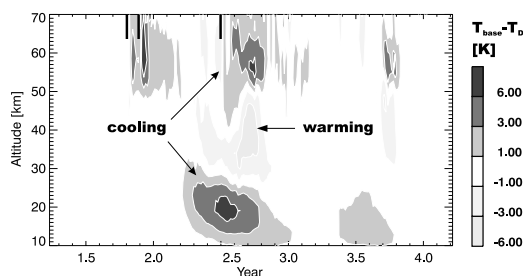


Figure 3. Modeled change of temperature between the Base run and model run “C” at 76°N. Positive values correspond to a cooling, negative values to a warming. Thick black lines indicate the occurrence of solar proton events.

40 km. Both warming and cooling are consequences of ozone changes. However, the lower stratosphere cooling is partially counteracted by additional warming of 1–2 K due to enhanced NO₂. The changes in temperature in turn affect the reaction rates of the gas-phase and heterogeneous reactions; the colder temperatures in the lower stratosphere favour liquid aerosol formation and heterogeneous reactions on liquid aerosols, while the warmer mid-stratosphere temperatures lead to lower ozone values due to faster ozone depletion and slower ozone formation reactions. Radiative heating and temperature also affect zonal and vertical wind speeds. Differences of up to 20 m/s between the Base run and model run “C” are calculated for the zonal wind speed by THIN AIR, with the largest changes in the sub-polar jet regions.

5. Conclusions

[9] We have shown that the structure of the magnetic field can have a large impact on the composition of the middle and lower atmosphere. The results shown here are based on realistic estimates of the magnitude of particle events, and a particular prediction for the structure of the magnetic field during a reversal. They show a considerable increase of particle induced loss of total ozone during a magnetic field reversal which is accompanied by an increase in surface UV-B radiation as well as changes in stratospheric temperature and circulation. For a more comprehensive study of the changes that can be expected during paleo-historic or future polarity transitions, more sophisticated models of the magnetic field structure during a reversal are necessary. The study also showed that the spatial as well as temporal distribution of losses of total ozone are dominated by the global transport pattern of the middle atmosphere. This might be significantly different during past and future reversals, i.e., due to changes in climate and wave forcing.

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